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Microclamping principles from the perspective of micrometrology - a review

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Abstract: This paper gives an overview of the field of clamping and gripping principles from the viewpoint of sample fixturing for dimensional metrology for microobjects. The requirements for clamping microcomponents that allow dimensional measurements are therefore explained before principles and solutions of microclamps as found in literature are reviewed and evaluated on basis of these requirements. Results show that there is no single superior clamping principle or method of implementation but rather several effective solutions for specific applications. The core value of this paper is the *link between requirements for sample fixturing in dimensional micrometrology and the many approaches already investigated in the field of microclamping*. A radar chart and a decision tree summarize and visualize the major aspects of this review. Finally, directions of future key research areas are suggested.

Keywords: clamping principles, fixtures, microtechnology, tactile dimensional metrology, capillary forces, microgrippers, vacuum, van der Waals forces, sample fixturing

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1 Introduction

Over the last two decades, enormous advancements in precision engineering and microtechnology have created a large variety of different gripping and clamping principles. In addition, the demands for topographical surveys of miniaturized objects have increased. Therefore, suitable gripping and clamping principles, and clamps for manipulation and measurement at micro- and nanoscales need to be identified [1, 2]. This paper systematically reviews microclamping principles from the viewpoint of application in dimensional metrology.

Especially for microscale objects, gripping and fixturing are still fields of active research because deformation and damage of the workpiece are more likely to occur and handling difficulties may arise because of increasing surface-to-volume ratios. In metrology, the quality and suitability of the clamping has a *strong impact on the uncertainty budget* and thus on the quality of the measurement results. Furthermore, microgripper and fixtures can be used for microassembly and as an integral part of microsystems (e.g. tool changers in microrobotics [3]).

In micromanufacturing, regular characterization of workpieces is rare; functional testing is more widespread but it gives only limited information in case of a failing workpiece. If characterization could be simplified (e.g. by optimized fixturing), then perhaps more manufacturers would be able to perform regular characterization and thus enhance their production quality [4, 5]. For subsequent manufacturing and characterization steps, using one fixture or a unified alignment may improve the process [4].

In contrast to microcomponent gripping, clamping and handling for manipulation and assembly, the clamping of microcomponents *for metrology* is still a topic that has not yet attracted sufficient attention. Microfixtures are worth analyzing because they provide fundamental functionality for micromanufacturing (e.g. production, assembly and measurement). Most of the reviewed papers do not directly refer to "clamping", "fixture" or "fixturing" but to grippers, microassembly, self-alignment, positioning systems, micromanipulation and the handling of microcomponents. Nevertheless, micrgrippers represent a very relevant state of the research in the field of microclamps. In the course of further miniaturization, there will be a need for fixtures at the microscale.

Figure 1 illustrates a comparison between grippers and fixtures regarding the purpose of the clamping force. Because – apart from moving of workpieces – the functionalities are identical, it is possible to interpret gripping principles as fixturing principles [6, 7]. Since the purpose of fixtures and grippers can be different, there may be different requirements regarding their design and implementation.

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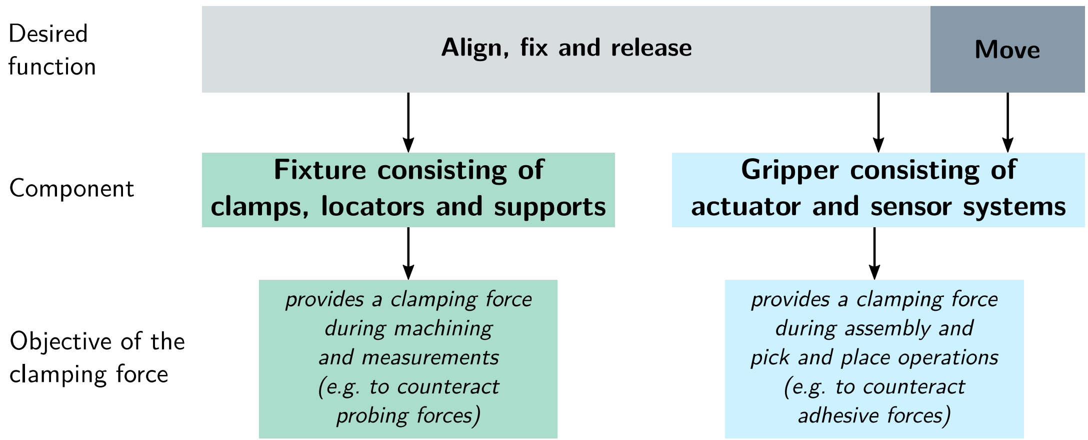

Figure 1: Comparison between grippers and fixtures regarding the main task of their clamping force [8, 9]

The left-hand side of Figure 2 sketches a setup typical for microassembly where a microcomponent (e.g. surface-mount technology component) is picked up and placed onto a macroobject (e.g. circuit board). A metrology setup sketched on the right-hand side of Figure 2 is currently being investigated at the Physikalisch-Technische Bundesanstalt (PTB) [10], where a tactile probe measures microgear components with a module ≤ 0.1 mm. The expected probing forces are in the range of several millinewtons. The goal is the integration of enhanced microprobes into commercial coordinate measuring machines (CMMs) [11] and the development of a microenvironment for the improved handling of the samples. Figure 3 shows typical microscale measurement situations.

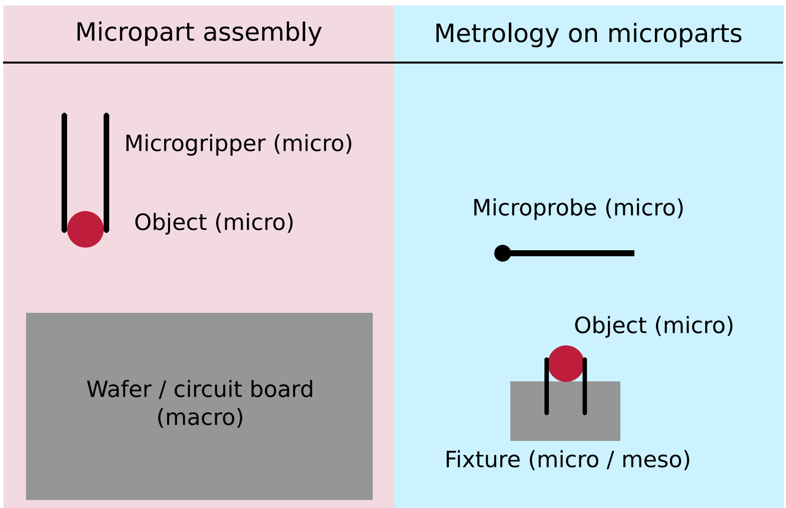

Figure 2: Comparative illustration of micropart assembly and metrology on microparts

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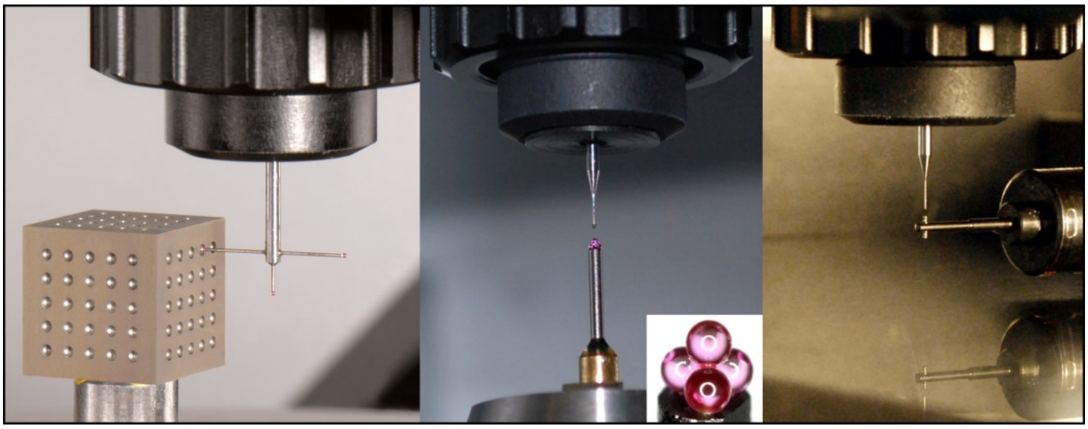

Figure 3: Examples for dimensional measurement situations on the micro coordinate measuring machine Zeiss F25 at the PTB. The samples are a calotte cube for CT calibration measured by a discontinued probe design (left), a micro-tetrahedron (middle) consisting of four ruby spheres with 300 µm diameter and a T-shaped microprobe for thread metrology (right). The diameter of the microprobe is 300 µm except for the measurement on the right where it is 125 µm.

Tichem et al. [12] define gripping as the process that "produces the necessary forces to get and maintain a part in a position with respect to the gripper". This definition holds true for fixturing as well. The clamping force counteracts other forces acting on the workpiece like:

1. Forces inherent to the measurement principle (e.g. probing forces).
2. Adhesion forces during pick-and-place procedures of the workpiece.
3. Forces from viscous friction with the environment (gas, fluid).
4. Inertial and gravitational forces (in some cases these forces can be neglected since they scale favorably with the length l; e.g. gravitation $F_g \sim l^3$ or moment of inertia $I \sim ml^2 \sim l^5$ where m is the mass of the object [13]).

Dominating forces during clamping at the macroscale are gravitational, centrifugal and machining forces [14]. Surface forces (no longer volume forces) predominantly influence typical microobjects with dimensions smaller than 1 mm [15]. Three major effects make clamping, handling and assembly more difficult at the microscale. First, electrostatic charging plays an important role and leads to relatively strong forces acting on microobjects. Second, van der Waals forces can rise to enormous magnitudes as seen in the context of bionics utilizing artificial gecko feet and gecko tapes with microscaled structures [16]. Third, capillary forces can strongly influence the motion of microobjects and, therefore, are utilized for the parallel self-alignment of electronic components [17].

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Wautelet [13] and Grutzeck et al. [18] state and compare scaling factors for different gripping principles including vacuum suckers, mechanical grippers, capillary forces nd adhesion. With progressing miniaturization, the effects of capillary forces and adhesion become more “effective” in comparison to gravitational and inertial forces because of their favorable scaling behavior. Boncheva et al. [19] give an extensive list of forces with significant magnitude in the microscale.

Fixtures can be distinguished by the following criteria [12]:

- Materials that can be processed (e.g. magnetic forces have no impact on plastic)
- Surface properties that can be processed (e.g. rough surfaces are difficult for vacuum suckers)
- Specific grip force characteristics that are implemented (e.g. maximum achievable force or decreasing force progression)
- Configuration and shape of force interaction surfaces
- Force control
- Cycle time (time needed for the processes of clamping and releasing)
- Accuracy in realizing clamp-to-workpiece relation
- Sensitivity to adhesive forces
- Purpose fixturing vs. fully flexible fixturing [4]
- Alignment features for the characterization operation on the workpiece or the fixture [4]

2 Microclamping requirements for metrology

From the perspective of dimensional micrometrology, a clamping principle must satisfy four key requirements which are discussed detailed in the following sections:

1. The clamping principle must not interfere with the measurement principle.
2. The clamping principle must minimize unwanted influence on the workpiece.
3. The clamping principle must allow robust and repeatable operation in the specified environment.
4. The clamping principle must allow the integration of features that simplify and improve the measurement.

In developing and selecting a clamping principle, demands to be considered come from the workpiece to be clamped, the clamp operation, the environment in which the clamp operation takes place [12] and the measurement principle. For example, contactless characterization methods may not require a physical fixturing at all [4]. Thus, we focus this review on contact-based metrology tasks.

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Furthermore, the difference between one-dimensional, two-dimensional and three-dimensional measurement tasks has great impact on the specific requirements. Currently, typical measurements of microstructures can be divided into three groups. First, one-dimensional and two-dimensional measurements of workpieces originating from microsystems technology. Here microscopic features tend to be integrated in macroscale workpieces (e.g. wafers), which can be clamped macroscopically [20]. Special measuring machines (e.g. atomic force microscopes, surface profilers) have been developed for these *metrology-on-one-surface* purposes. The second group comprises three-dimensional measurements of macroscopic workpieces that possess microscopic features. These components can also be clamped with macroscopic means. Third, objects like microscopic spur gears that are not only difficult to handle but also difficult to measure reliably and traceable at that scale. The small number of found literature in this area leads us to the presumption that these objects normally are not characterized by routine dimensional measurements in industrial production so far since measuring machines [21] and mature handling systems like grippers and fixtures for micrometrology are missing.

2.1 Interference with the measurement principle

The most important criterion for microclamping principles is to avoid interference with the measurement principle which would eventually lead to a greater measurement uncertainty. Clamping principles differ fundamentally for microscopic and macroscopic objects; and interferences between the clamping and the measurement are mainly notable for microclamping. Mechanical clamping that prevails for macroscopic workpieces has manageable interferences whereas electrostatic clamping forces may have impact on the measurement process.

Interferences can be differentiated in signal interferences and physical interferences. Signal interferences impede the recording, transfer and processing of measurement signals. For example, typical microprobes [10, 22, 23] use piezoresistive or capacitive sensors to detect the deflection of the probe tip. Magnetic fields may interfere with the sensor system and alter the signal. Regarding dimensional X-ray computed tomography (CT) measurements, the radiation absorption of the clamp should be as low as possible to obtain good results.

Physical interferences comprise the accessibility for tactile probes and cameras (also vital for multi-sided machining). Obviously, accessibility for probing and vision is a decisive criterion. Important is the level of accessibility (e.g. the number of surfaces covered by the clamp). Even when tactile probing of a mechanically clamped workpiece is possible, re-clamping is inevitable if the contact surfaces allocated by the jaws must be measured. Unfortunately, this introduces a new set of errors that worsens accuracy. Accessibility for cleaning and user interaction is also important since microobjects are naturally difficult to handle. Some measurements require a

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special environment (e.g. vacuum environment for scanning electron microscopy [24]) which must be considered in the design process of the clamping.

2.2 Influence on the workpiece

Minimized influence on the workpieces is essential for microclamping since objects at the microscale are very fragile. Plastic deformation or scratching must not occur at any moment during fabrication, assembly and characterization. When measuring microscopic features (particularly when measuring with small probe tips), the influence of the surface roughness and waviness [25, 26] on the measurement results becomes visible. For macroscopic tactile measurements, the probe acts as a mechanical filter which suppresses these influences [27]. This leads to high requirements regarding the distribution and deployment of the clamping forces since they can considerably alter the local surface roughness.

During characterization, the workpiece is influenced by clamping forces and forces due to the measurement principle. The elastic deformation of the workpiece distorts the measurement result in an unpredictable way. Deformation originating from the clamping can be avoided or minimized by:

- Small clamping forces and force control
- Uniform force distribution over a large surface area
- Form closure
- Compliant mechanisms that adapt their coupling surfaces to fit the surface of the workpiece in an optimal way (e.g. soft grippers, flexure hinges). This is helpful to compensate variations in the parts

Customization of the gripper or fixture design may lead to reduced deformation due to metrology forces (e.g. optimized flux of forces by reducing the lever arm of the probing force or additional supports).

Contamination may have a negative impact on measurement and the following assembly processes thus diminishing yield and accuracy. The smaller the dimensions of the workpiece, the smaller are the particles that could possibly interfere with the measurement. Wear strength is a critical factor to reduce particle production due to abrasion. Since tactile microprobes are more fragile, more prone to functional impairing contamination, and costlier than their macroscopic counterparts, contamination control is an essential issue for microclamping.

The clamping should avoid of over-constrained workpieces. Kinematic and semi-kinematic design rules can be applied to avoid over-constraining and optimize possible solutions (e.g. in terms of repeatability). Over-constraining of workpieces

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may yield a higher measurement uncertainty; moreover, the following negative aspects may occur:

- Non-repeatable positioning of the workpiece
- Thermal changes may lead to geometric expansion, thus to internal stress
- Higher accuracies of the clamping may be needed to achieve comparable accuracy

Since the thermal expansion of the fixture may evoke stress in the samples, the clamping should cause minimal temperature changes. Thus, the fixture or gripper material should have a small thermal expansion coefficient for long-term stability, i.e. keep long-term expansion to a minimum (e.g. *Zerodur* or *Invar*). However, temperature stability *of the microscaled sample* is not as critical as in the macroscopic case. For example, Albers et al. [28] state tolerances of ± 5 µm for microgears "on all their relevant features, corresponding to about 10 % of their nominal measures". In comparison, a temperature shift of 1 K leads to a negligible length expansion of 1 nm (100 µm initial length, steel with an expansion coefficient of $\alpha = 10 \cdot 10^{-6}\mathrm{K}^{-1}$).

2.3 Robustness and repeatability

Workpieces may deviate in their form; contamination from various sources may occur. Thus, an implemented principle should be resistant to such influences. Especially for inspection during production, reliable and robust fixtures ensure productivity. Routines should indicate that the fixture is not working properly to prevent incorrect measurements (self-verification capability to ensure quality [29]). Error detection and debugging at the earliest stage are desirable. Often used characteristic parameters for reliability are mean time to failure (MTTF), mean time to repair (MTTR) and the failure rate. A tool to ensure reliability and minimize failure costs is the failure mode and effects analysis (FMEA) [30, 31].

A high repeatability after relocation of the workpiece is mandatory for high-precision measurements. Repeatability is defined as the measurement precision under a set of repeatability conditions (same procedure, measurement system, location etc.) [32]. Repeatability is important to obtain consistent results (e.g. repeated measurements of standards). Error separation techniques (e.g. reversal techniques [33]) rely on repeatability to eliminate systematic measurement deviations.

High stiffness (and high damping) of clamps prevents the workpiece from deviating in its position [34]. The required stiffness depends on the workpiece itself (material, stiffness etc.), the process forces occurring and the desired precision. Defined clamping forces and force control is important to avoid deformations.

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2.4 Features that simplify and improve the measurement and broaden the range of application

The measurement of datum features at the beginning of a characterization defines the relation between the workpiece coordinate system and the machine coordinate system [35]. This mapping aims to eliminate misalignments and offset errors. However, datum features are sometimes missing when measuring microcomponents. One reason could be that there are no suitable features or that these features cannot be measured. For example, the measurement of spur gears requires the definition of an axis for evaluation. If the fixture uses the inner diameter of the spur gear for clamping, this feature cannot be used for the definition of the workpiece coordinate system. However, if the workpiece-to-fixture position is well-known, one may use datum surfaces on the clamp to set up the coordinate system. Thus, self-centering and self-alignment are important features (see Figure 4). For most applications, self-alignment is sought. Rotationally symmetric workpieces only need centering. Ideally, a precise centering mechanism may prolong the lifespan of the tactile probe because deflections when setting up the workpiece coordinate system are minimized. The precise alignment of the workpiece is a time- consuming and difficult task. Bergander et al. [36] state that – for manual alignment – it takes specially trained technicians 15 minutes to achieve an accuracy of about 1 µm. Fixtures that align and center workpieces save time and costs. Additionally, modern CMMs possess computer-aided workpiece position compensation. Sanchez [37] recommends the use of V-groove structures and datum points to guide the microcomponents into the desired positions and orientations.

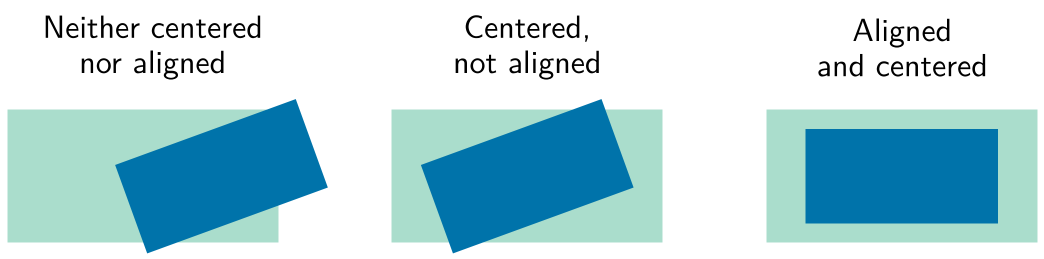

Figure 4: Difference between centering and alignment

Automation of the clamping process reduces the influence of the operator which normally leads to a higher repeatability. In the context of industry 4.0 [38], the clamp could be extended to a cyber-physical system that communicates with the measuring system and thus provides additional process and sensor data. This may be especially important for microclamping since examinations of the setup by the operator are limited due to the small sizes.

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Intermachine transport is required since most fabrication steps rely on unique special purpose machines [37]. A transportable clamp would be ideal since no repositioning would occur and valuable time would be saved. An important issue is standardization (e.g. standard carriers). Since micro-sized parts are often customized and production volume is small, it is beneficial to possess a flexible clamp. Considering the current state of art, however, this is not realistic. Furthermore, the range of materials supported by the clamp constrains the suitability of different clamping principles. Highly specialized micrograppers capable of handling a very small set of workpieces are common in today's industry.

Many microcomponents are fabricated in cleanroom laboratories. These devices possess functional elements with dimensions similar to particles that are found in ambient air. Compatibility to cleanroom specifications is achieved by low particle emissions, chemical resistance (e.g. to solvents) and cleanability.

3 Overview of microclamping principles

In Figure 5, clamping principles found in the literature are categorized as being of the type "form closure", "traction", "adhesive" or "contactless".

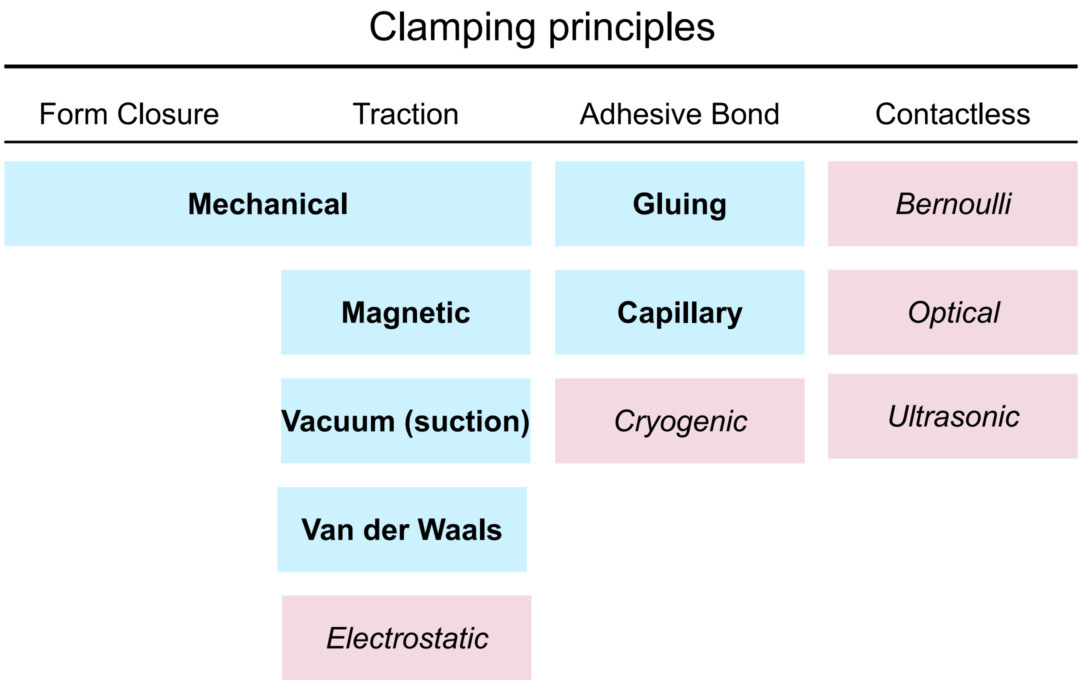

Figure 5: Categories of clamping principles (blue and boldface: discussed as principles suitable for clamping in metrology, red and italic: not suitable for metrology)

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The clamping principles depicted in red color lack suitability for metrological applications for the following reasons:

- Optical tweezers (e.g. laser grippers) generate forces, which are too small [39].
- Adequate electrostatic forces require high voltages. This leads to unintended charges possibly up to the destruction of components, particle attraction and possible influences on the surrounding equipment including the measurement system. Li and Chew [40] present a review of electrostatic, piezoelectric and electrothermal microactuators.
- Cryogenic grippers exert highly undesired temperature shifts. An introduction to ice or cryogenic grippers is shown in [41, 42].
- Aerodynamic levitation (Bernoulli, air cushion) and ultrasonic levitation (standing wave, squeeze film) are not discussed because of the lack of control of the gripping forces; their instabilities and their difficult setup procedures. Some contactless principles need the workpiece to be suspended in liquid, which restricts their scope of application [43].

We consider the six remaining microclamping principles (depicted in blue color in Figure 5) suitable for application in metrology. Their principles of operation are sketched in Figure 6 and discussed in the following sections.

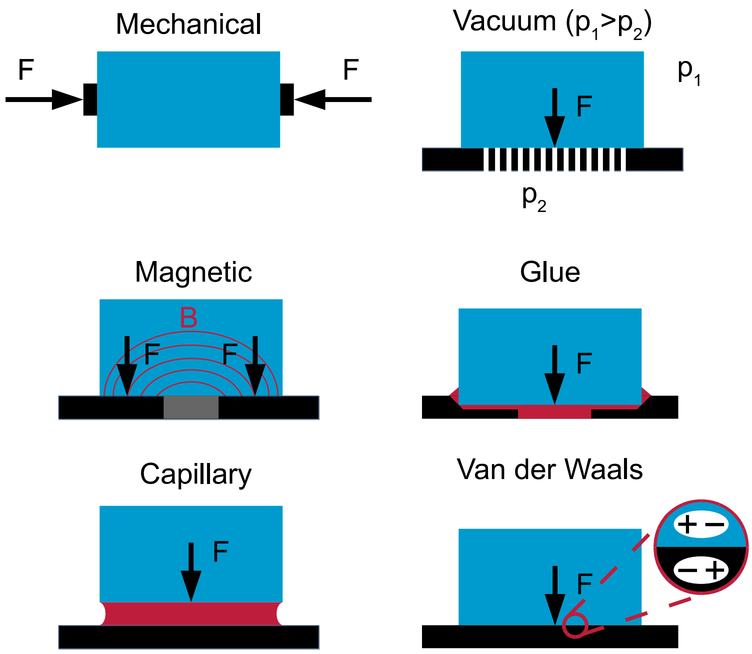

Figure 6: Schematic overview showing the six clamping principles discussed in more detail

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Since surface interactions play a major role in most of the principles, coating is often a favorable way to enhance effectivity (e.g. by conductive, hydrophilic or ferromagnetic coating) [44]. Fantoni et al. [1] give a good overview of state-of-the-art grasping devices and methods in general.

3.1 Mechanical clamping

Mechanical clamping is one of the most used principles at the macro- and microscale. Mechanical grippers grasp complex geometries (e.g. gears); difficult environmental states like high/low humidity and material properties do not affect the principle. At least two gripping surfaces are needed [45].

The gripper's actuation principle can be different from the mechanical clamping principle. For example, mechanical tweezers can be actuated electrostatically; however, they are attributed to the class of mechanical grippers [46, 47].

Figure 7 gives an overview of actuation principles used for gripping, sensor systems and the releasing strategies for mechanical grippers as found in the literature. All combinations of actuators, sensors and release strategies are in principle possible. This leads to many different mechanical microgripper designs.

Shape memory alloys (SMAs) and electrothermal actuation are likely to influence the measurement due to their temperature shifts. Moreover, SMAs are difficult to control because of their thermomechanical nonlinearities [48]. Minimizing the contact area overcomes sticking effects but introduces high stresses to the workpiece. A release in fluid is only applicable if there is a value added by the fluid (e.g. lubrication). Otherwise, there are more suitable release strategies. Release via immersion in a fluid counters electrostatic and capillary forces but unfortunately, in most cases, it is not applicable.

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Mechanical clamping

Actuation principle	Sensing system	Release strategy
Piezoelectric	Piezoelectric	Vibration
Shape memory alloy	Piezoresistive	Minimized contact area
Electrothermal	Magnetic	Third auxiliary end effector
Electrostatic	Capacitive	Inertial effect
Electromagnetic	Optical	Coating
Fluidic	Vision-based	Release in fluid
	Electro-active	Gluing
		Rolling

Figure 7: List of mechanical clamping concepts

In mechanical clamping, forces are scalable and can be applied at the desired level. A drawback is the focused force application [45] that leads to high local stresses deforming and damaging the workpiece [49].

Centering principles for mechanical clamping require highly sensitive sensors and control algorithms. Positioning in the direction of the grippers is very precise. A drawback with tactile mechanical clamping is the surface area, which is no longer accessible, where contact between the clamp and the workpiece occurs. Spur gears, for example, have their functional surface (teeth) at places where grippers would typically touch. Measurement is then impossible and re-clamping is necessary. This process affects the cycle time and especially the measurement uncertainty [45]. The process cycle time is heavily dependent on the actuator principle (e.g. piezoelectric actuators react within milliseconds whereas shape memory alloys need more time for heating) [45].

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High precision measurements require cleaning to minimize the particle contamination of the workpiece and microprobe. Particle spreading effects also play a relevant role. Particle generation may occur because of abrasion during contact [45]. Mechanical clamping can use either form closure or traction to fix a workpiece's position. A wide variety of shapes is available to achieve form closure. Nevertheless, the design and manufacturing of these micromechanical grippers is costly and complex [49].

In contrast to pick-and-place applications, the problem of unwanted *sticking* of workpieces onto the grippers is only a minor disadvantage because it does not affect the measurement in a direct way. Several principles for the release of microcomponents have been considered, potentially overcoming sticking effects. They include the induced vibration of the gripper [50, 51] and a third auxiliary microgripper arm [52]. Advantages and disadvantages of the actuation principles can be found in [53].

Mechanical microgrippers often use flexure hinges to form movable parts. They possess very low friction and no backlash. Compliant principles (e.g. flexure hinge [54]) are associated with an inherent positioning uncertainty. Even in a simple setup where two springs resemble the compliant mechanism (see Figure 8) two disadvantages arise:

1. The compliant structures (e.g. mechanical jaw grippers with flexure hinges) must possess an identical spring constant c. This can be realized by identical material properties and shapes but is difficult to maintain if material fatigue plays a role.
2. If there is friction with a coefficient μ, there will be an unknown displacement which can reach a maximum value u_{max} depending on the spring constant, friction coefficient, the mass of the workpiece m and acceleration due to gravity g as follows:

$$u_{max} = \mu \frac{m \cdot g}{2 \cdot c}$$

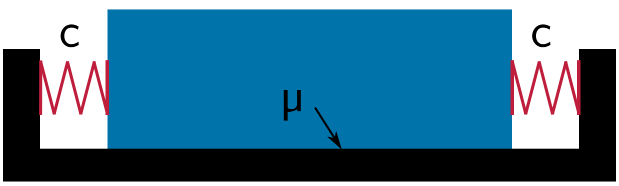

Figure 8: Schematic sketch of a compliant clamping principle

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On the other hand, compliant clamps can prevent high contact forces from accidental collisions with microprobes. This can prolong the service life of probes.

Two special clamping methods that we categorized as “mechanical” are molding workpieces in low-melting metals and the use of magnetorheological fluids which solidify if a magnetic field is activated [55, 56].

3.2 Gluing

To clamp a micronized part, the adhesion effect of an initially liquid medium can be utilized. For example, UV curable pressure-sensitive adhesives can clamp and release wafers for dicing [57]. Thermal glues solidify at room temperature and survive numerous cycles of solidification-liquefaction [3, 55]. Dröder et. al include wax as clamping medium [58]. Most adhesives inherently take much time to solidify and contaminate the workpiece.

High cycle times, creep and the unwanted contamination of the workpiece after detaching are disadvantages of this principle [3]. Advantages – regarding metrological applications – are flexibility, inherent damping of the adhesive bond, uniform force distribution, unrestricted free access for five-sided characterization or machining, high pull-off forces [59] and the wide variety of glues (e.g. conductive/non-conductive, high/low peel resistance, light-curing, solvent-based etc.) [60, 55].

3.3 Magnetic clamping

Magnetic clamping is limited in its use because clamping forces – compared to other actuation principles – are weak [61, 58].

Magnetic clamps can fix ferromagnetic workpieces in a firm non-distorting manner. Magnetic clamps can operate in harsh environments (robust to air, water, vacuum). In contrast to electrostatic actuation, magnetic actuators require currents but only moderate voltages [62].

The use of magnetic clamping is limited since the resistive heating of the electromagnets causes the thermal expansion of the material.

3.4 Capillary forces clamping

Arutinov et al. [17] and Lambert et al. [63] show that surface tension and capillary forces can be used to manipulate microcomponents. The clamped material should be hydrophilic or oleophilic. Self-alignment via capillary forces is a beneficial side effect [1] and high accuracies at a minimal expense can be achieved [64, 65].

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Böhringer [66] gives a comprehensive overview of self-assembly. Berthier et al. [64] state that capillary forces are independent of the workpiece geometry for small shifts. Capillary forces are dependent on intrinsic properties (e.g. physical properties) and boundary parameters (e.g. environmental characteristics) [61]. Furthermore, capillary forces may be modeled and simulated [67]. This approach is attractive when precision is good enough to make position sensing and control obsolete.

Figure 9 illustrates the formation of a liquid bridge during a simple pick-and-place routine.

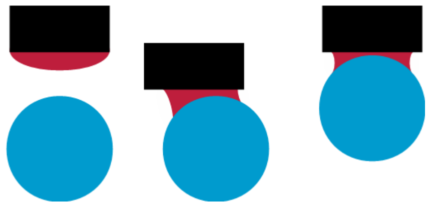

Figure 9: Sketch of a pick-and-place process with capillary forces

The advantages of capillary forces are their "favorable downscaling law, a compliant behavior, the capability of grasping small and light components in a wide range of materials and shapes and the ability to deal with delicate components as the meniscus between the gripper and the object acts as a bumper" [67]. Design rules for a capillary gripper are extracted by Lambert and Delchambre [68]. Butt and Kappl give a detailed overview of capillary forces [69].

Capillary forces are *excellent at picking up but lack in releasing*. Several works address this problem and potential solutions include schemes based on vertical/horizontal component release, evaporation, mechanical needles and electrowetting [43, 49, 39, 17].

Currently, the low clamping force and time stability make this clamping principle only worth considering for non-contact metrology tasks.

3.5 Vacuum clamping

Vacuum clamps can operate at various conditions but obviously not in vacuum. They can clamp all materials except for porous objects. Their disadvantages are the small effective areas [55] and the poor scalability of the clamping force, which may even harm the workpiece. Vacuum suckers are inexpensive [70], moderately precise [45, 71] and may offer limited self-alignment (e.g. via a conical shape of the tool) [72]. In general, the clamping time is moderate due to the generation of the negative pressure. Problematic particle generation may occur because of abrasion during contact [45, 73].

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Vacuum clamping for microcomponents was successfully implemented several times, e.g. [74]. In general, it is difficult for grasping objects smaller than 100 µm [75].

Suction forces dominate in magnitude over electrostatic, van der Waals and capillary forces [76]. Releasing of the workpieces may be supported by blow-out (moderate positive pressure blast), coating of the tool, using the inertial force of the component, rolling the component on the release plane or mechanical extensions [70]. In industrial settings, a compressed air supply is often available and vacuums can be generated via Venturi tubes at low costs.

3.6 Van der Waals force clamping

Van der Waals forces occur because of "fluctuations in the electric dipole moment of atoms and their mutual polarization" [77]. For example, geckos have extraordinarily adhesive feet caused by intermolecular surface forces [78].

Polyurethane materials can firmly grip both micro- and macro-sized workpieces with low roughness (root-mean-square surface roughness ≤ 35 µm) [79]. Murphy et al. [80] have found that a 1 cm x 1 cm polyurethane flat material can exert over 1 N of van der Waals forces on smooth surfaces [79], which is sufficient for most applications in tactile dimensional metrology. Adhesion forces like van der Waals forces are influenced by ambient humidity [81, 82].

Overall, the adhesive forces due to van der Waals interactions are difficult to estimate. They mainly depend on the material type, the geometrical configuration of interacting materials, the topography of the interacting surfaces (surface roughness) and environmental conditions [83]. Matope [83] gives a comprehensive overview of van der Waals forces in microhandling.

3.7 Hybrid approaches

Sanchez-Salmeron et al. [84] conclude in their study that combination of different clamping principles is recommended to increase flexibility. No clamping principle fulfills all the design requirements. This leads to a demand for hybrid solutions for microclamps in metrology. Using hybrid clamps can combine the advantages of different principles [85, 3].

Varadarajan and Culpepper designed and tested a macroscopic dual-purpose positioner-clamp for precision six-axis positioning and precision clamping. The combination of positioner and clamp characteristics could be interesting for microsystems to expand the scope of application [86]. For example, these dual-purpose clamps could be used for the assembly of microoptical elements where fine positioning and tuning is vital for functionality [87].

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4 Comparison of microclamping principles

A radar chart illustrates eight parameters to provide a visual comparison of clamping principles (see Figure 10). High scores (outer area) resemble a clamping's good performance. The fulfillment level of the principles varies substantially regarding the single parameters. However, when comparing the overall performance by computing a *virtual* "mean level of performance", the differences between the clamping principles are less obvious.

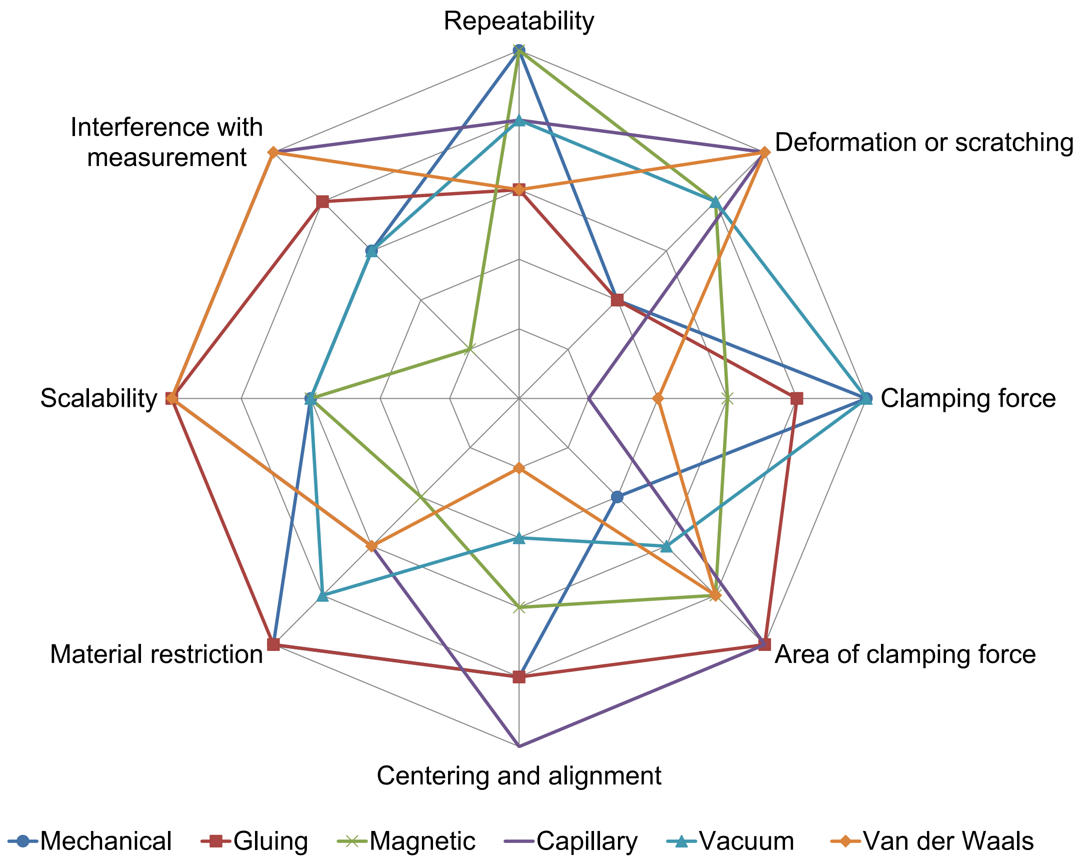

Figure 10: Comparison of microclamping principles via radar chart

The appendix comprises a table that displays the underlying data used for the radar chart.

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5 Conclusion and outlook

All clamping principles evaluated in this review have substantial drawbacks, which limit their usage. The choice of the clamping principle heavily depends on the application: workpiece material and surface properties, measurement system and task, size and geometry of the workpiece.

To find an adequate solution for a given clamping challenge in metrology, one can orient on the performance parameters as evaluated above for the six different clamping principles. Figure 11 contains a decision tree by which a sequence of closed questions (yes-no questions) can guide the way to the selection of microclamping principles.

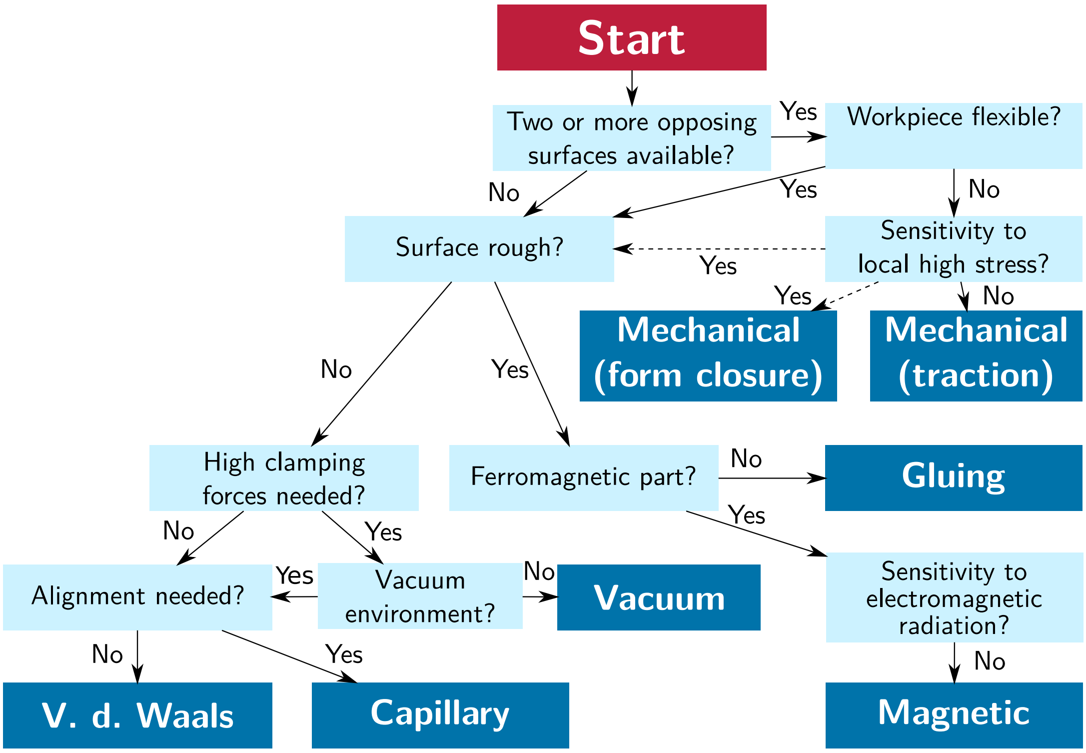

Figure 11: Decision tree for the selection of a microclamping principle for micrometrology

The decision tree depicted in Figure 11 might be further developed to an expert system. Fantoni et al. [88] proposed a method for supporting the selection of robot grippers. Potentially, their expert system could be extended to the microscale and be considered for metrological applications.

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Key areas which need further attention in research are:

- Customized clamping solutions for specific workpieces and characterization processes
- Integration into modular and reconfigurable micromanufacturing systems
- Force and position sensing
- Clamps with adjustable stiffness to achieve form closure without deformation

We regard research on microclamps as an important aspect of metrology for small objects and expect it will lead to:

- Improvements in terms of reliability, standardization and self-alignment
- Hybrid clamping solutions
- Maximizing clamping forces for contactless principles
- Flexibility regarding the workpiece (shape, material, surface)
- Sensing, control and connectivity (smart systems, industry 4.0)
- Process automation (intelligent algorithms, machine learning)

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7 Conflict of interest declaration

Hereby the authors declare no undisclosed funding source and no relationship that may pose a conflict of interest.

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9 List of figures

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10 Appendix

Table 1 summarizes the findings of the review in the form of a scorecard. A qualitative evaluation is given (++ equals *excellent performance*, - - equals *poor performance*). Grey shadings indicate the best performances regarding each parameter.

Table 1: Scorecard of microclamping principles

Principle / Parameter	Mechanical	Gluing	Magnetic	Capillary	Vacuum	Van der Waals
Minimal Workpiece Dimensions	++ (2.7 µm [89])	+ (depending on drop dispensing and microobject handling)	++ (no restriction)	+ (50 µm [90])	+- (50 µm [91])	++ (no restriction, 500 µm [79])
Cycle Time	++ (140 ms [92] via SMA, 11 ms via bimetal [93], depending on actuation principle)	- -	++ (0.4 s [84])	- - (500 ms [90], 800 ms [39])	++	++
Dependence of	++	+- (depending on glue,	++	+- (depends on humidity and surface	- (no vacuum)	- (depending on

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Environment		e.g. temperature-dependent)		roughness [94])		humidity)
Deformation or Scratching	- (at contact points, critical because small area)	- (creep)	+ (depending on workpiece geometry, uniform force distribution)	++	+ (at contact areas)	++
Contamination	- (possible, due to wear and particle deposition on the gripper)	- - (likely due to adhesive residues)	- (possible due to attraction by magnetic field)	- (fluid residue)	- (possible, due to wear and particle deposition on the gripper)	++
Flexibility	+ (jaw opening range up to 515 µm [95], flexible jaw geometry / tool change [96], material [95])	++ (high variety of glues available)	+	+	+-	++
Repeata-bility	++ (typical accuracy in the range of 0.1 µm -10 µm [84])	+ (1 µm for each direction [3])	++ [84]	+ (± 20 µm [89], 0.9 µm [97], 0.2 µm [98])	+ (± 5 µm [99])	NA
Centering and Alignment	+ (via form closure, asynchronous contact of fingers may introduce errors [100])	++ (via surface tension)	+-	++ ([101], via surface tension)	- (difficult in most of the cases)	- - (no inherent centering or alignment)

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Material Restrictions	++ (none)	++ (right glue selection provided)	- (ferromagnetic materials only [100])	+- (surface treatment may be necessary [98], hydrophilic or oleophilic [102, 103])	+ (smooth surfaces needed)	+- (smooth surfaces needed, high Hamaker constant [102])
Interference with the Measurement	- (jaws cover at least two surfaces)	++	- - (electromagnetic radiation)	++	+- (air flow could attract particles)	++
Scalability	+- [18]	++ [18]	+- [13]	++ [18]	+- [18]	++ [13]
Clamping of Complex Geometries	+- (at least two clamping surfaces required)	++	+ (one Contact surface needed)	++	+ (one contact surface needed)	+ (one contact surface needed)
Clamping Force	++ (35 mN via SMA [92], 59 mN via two-way SMA [104], 5 N via fluid actuation [89], 1 N via piezoelectric actuation [95], 18 mN via magnetic actuation [95])	++ ([96], 10 mN to 50 mN [3])	++ ([96], tens of mN [87])	- - (1.2 mN [101], 213 µN lifting force [39])	++ [84]	+- (1 N [80], depending critically on surface structure [96], 100 nN per gecko hair [3])
Area of Clamping Force	- (depending on gripper, mostly small [105])	++ (glue fits in rough surfaces)	+	++	+	+

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Possibility of Control (Force/Position)	++ (force and position control available [106, 107], important for fragile parts =[100]=[100])	- (glue selection has impact on overall force)	- (force modulation possible)	+- (self-alignment makes position control redundant, force control not possible)	- (force modulation possible)	- - (no control possible)
Main Drawbacks	deformation, two workpiece faces for jaws required	high cycle time, workpiece contamination	interference with measurement possible, release problem due to the remanent force [84]	workpiece contamination, small forces	dependence on smooth surface structure, external air supply	highly dependent on surface structure

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